MIKE SHE for Integrated Water Resources Management and Planning

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Abstract

Many water resources projects are affected by the interaction of surface water and sub-surface systems, where changes in one system have a significant influence on the other. Examples of such problems include those in which head changes in a groundwater system cause local changes in the rate of seepage to the rivers and thereby influencing water availability or environmental conditions of surface water during dry periods. More complex situations occur when conjunctive use of surface water and ground water are delivered to irrigation areas by complex operating rules and subject to return flow to water systems downstream.

In recent years more accurate and sophisticated approaches to model water resources systems as single integrated systems, where the complex impact of process changes in various parts of the hydrological cycle can be evaluated, has become increasingly common in water resources management and planning.

This paper presents the MIKE SHE modeling system, which over the past 20 years has been applied World-wide for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater. This system has evolved into a very versatile tool that can be tailored according to local project objective and availability of information. The presentation will show examples of a variety of applications ranging from conjunctive water use studies to groundwater vulnerability assessments.

***Keywords**: MIKE SHE modeling water resources management*

1 Introduction

Hydrologic modeling has become an essential tool in water resources management and planning, with two fundamental roles. The first role is to improve our understanding of the physical, chemical and biological processes within a river basin or watershed and the way they interact. The second, more practical role is to apply this understanding to manage and protect our water resources and the water environment. Many challenges remain on both fronts.

In this paper, we look at a comprehensive watershed-modeling tool MIKE SHE. MIKE SHE can treat many water management issues in an integrated fashion, at a wide range of spatial and temporal scales. The general background of the MIKE SHE model including a range of applications that document the flexibility of its process-based approach is presented. Finally, we provide a summary of the ongoing developments for MIKE SHE is provided. Demonstration versions of MIKE SHE can be downloaded from the MIKE SHE website, www.mikeshe.com, along with more detailed technical information. A review of the hydrologic processes included in the MIKE SHE modeling framework and the mathematical descriptions of these processes is presented in a separate paper.

2 The role and challenges of hydrologic modeling of watersheds

The water resources around the world are under increasing pressure due to rapid population and economic growth, aggravated by a lack of coordinated management and governance (UNESCO, 2003). Water shortage, deteriorating water quality and flood impacts are among the most urgent problems that need attention. However, surface water and groundwater have been, by tradition, managed separately - often in completely different branches of government. It is now recognized that water resources problems cannot be treated in isolation. The problems are seldom isolated and their solution requires a holistic approach to water management that must address different, often conflicting, demands for water. Problems like wetland protection or the conjunctive use of surface water and groundwater resources require the integrated management of surface water and groundwater together with the water chemistry and ecology. Nor does water movement follow political boundaries, which creates conflicts and further fragments management activities, (Jensen et al., 2002, Refsgaard et al., 1998). Increasingly, water resources are being managed on a river basin basis, while addressing problems at the local scale. For example, the European Water Framework directive requires water resources to be managed independent of international boundaries (Directive 2000/60/EC of the European Parliament and of the Council). In Canada, the Ontario provincial government is implementing watershed-based source protection for drinking water resources (Smith et al., 2004).

Changing to a river basin-based water management system challenges not only our management structures, but it also requires new and more sophisticated tools. Traditional groundwater and surface water models were not designed to answer questions related to conjunctive use of groundwater and surface water, water quality impacts of surface water on groundwater, impact of land-use changes and urban development on water resources, and floodplain and wetland management, many complex issues within the same basin. Instead, fully integrated hydrologic models of the watershed behavior are required. These models must not only describe the water flow processes in an integrated fashion, but they must also be able to provide answers about the movement of sediment, chemicals, nutrients, and water-borne organisms and their role in watershed habitats and ecology.

The increasing demand for water resources also challenges our ability to understand and describe the underlying hydrologic processes. For example, the simple fact is that the spatial scales of the processes involved range over many orders of magnitude (e.g. from the size of soil pores to regional groundwater aquifers of many 1000's of square kilometers). The inherent heterogeneity of natural systems makes it difficult to represent these processes accurately, (Grayson and Blöschl, 2000). The impacts of human induced changes due to agriculture, urban development, and water pollution are by no means fully understood. Furthermore, the growing focus on climate change has provoked increased research into understanding the complex feedback between the atmosphere and the terrestrial hydrological cycle.

2.1 Hydrologic modeling and MIKE SHE

In the hydrological cycle, water evaporates from the oceans, lakes and rivers, from the soil and is transpired by plants. This water vapor is transported in the atmosphere and falls back to the earth as rain and snow. It infiltrates to the groundwater and discharges to streams and rivers as baseflow. It also runs off directly to streams and rivers that flow back to the ocean. The hydrologic cycle is a closed loop and our interventions do not remove water; rather they affect the movement and transfer of water within the hydrologic cycle.

In 1969, Freeze and Harlan (Freeze and Harlan, 1969) proposed a blueprint for modeling the hydrologic cycle. In this original blueprint, different flow processes were described by their governing partial differential equations. The equations used in the blueprint were known to represent the physical processes at the appropriate scales in the different parts of the hydrological cycle.

From 1977 onwards, a consortium of three European organizations[1] developed, and extensively applied, the Système Hydrologique Européen (SHE) based on the blueprint of Freeze and Harlan (Abbott et al., 1986a & b). The integrated hydrological modeling system, MIKE SHE, emerged from this work (see Figure 1).

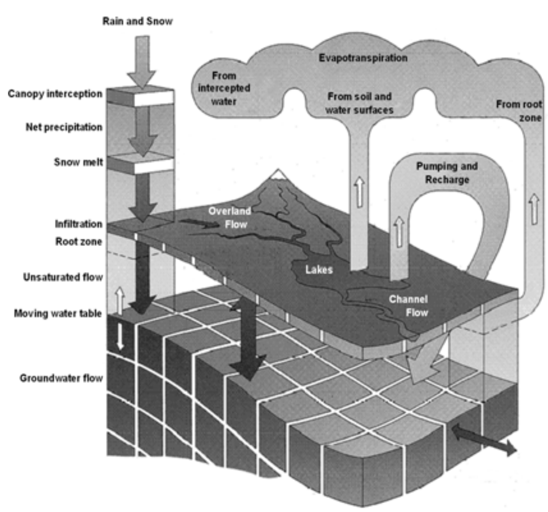

Figure 1. Hydrologic processes simulated by MIKE SHE

Since the mid-1980's, MIKE SHE has been further developed and extended by DHI Water & Environment. Today, MIKE SHE is an advanced, flexible framework for hydrologic modeling. It includes a full suite of pre- and post-processing tools, plus a flexible mix of advanced and simple solution techniques for each of the hydrologic processes. MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data and the modeler's choices, (Butts et al. 2004).

[1] The Institute of Hydrology in the United Kingdom (now called Centre for Ecology and Hydrology), SOGREAH in France, and the Danish Hydraulic Institute in Denmark (now called DHI Water & Environment)

The MIKE SHE user interface allows the user to intuitively build the model description based on the user's conceptual model of the watershed. The model data is specified in a variety of formats independent of the model domain and grid, including native GIS formats. At run time, the spatial data is mapped onto the numerical grid, which makes it easy to change the spatial discretisation.

MIKE SHE uses MIKE 11 (Havnø et al. 1995) to simulate channel flow. MIKE 11 includes comprehensive facilities for modeling complex channel networks, lakes and reservoirs, and river structures, such as gates, sluices, and weirs. In many highly managed river systems, accurate representation of the river structures and their operation rules is essential. In a similar manner, MIKE SHE is also linked to the MOUSE sewer model (Mark et al, 2004, Lindberg et al, 1989), which can be used to simulate the interaction between urban storm water and sanitary sewer networks and groundwater. MIKE SHE is applicable at spatial scales ranging from a single soil profile, for evaluating crop water requirements, to large regions including several river catchments, such as the 80,000 km^2 Senegal Basin (e.g. Andersen et al., 2001). MIKE SHE has proven valuable in numerous research and consultancy projects covering a wide range of climatological and hydrological regimes, many of which are referenced in Table 1.

Table 1. Selected literature references for application areas of MIKE SHE.

Application areas	References
General MIKE SHE References (Distributed hydrologic modeling and applications)	Abbott & Refsgaard (1996), Abbott et al. (1986 a & b), Havnø et al. (1995), Refsgaard et al. (1998), Refsgaard & Storm (1995), Storm & Refsgaard (1996),
River Basin Management and Modeling	Andersen et al. (2001), Christensen (2004), Henriksen et al. (2003), Jain et al. (1992), Jensen et al. (2002), Refsgaard & Sørensen (1994), Refsgaard et al. (2003, 1998, 1992), Sandholt et al. (1999), Vazquez. (2003)
Integrated Surface Water and Groundwater	Graham & Refsgaard (2001), Kaiser-Hill (2001), Olesen et al. (2000), Refsgaard et al. (1998), Sørensen et al. (1996)
Groundwater Modeling	Christiaens and Feyen (2001, 2002), Madsen & Kristensen (2002), Sonnenborg et al. (2003), Refsgaard et al. (1998)
Groundwater Pollution, Remediation and Water Quality Modeling	Brun and Engesgaard (2002), Brun et al. (2002), Christiansen et al. (2004), Hansen et al. (2001), Refsgaard et al. (1999, 1998), Sørensen and Refsgaard (2001), Thorsen et al. (1998)
Wetlands	Copp et al. (2004), Jacobsen et al. (1999), Lasarte et al. (2002), Refsgaard et al. (1998, 1994), Refsgaard & Sørensen (1994), Thompson et al. (2004), Yan et al. (1999)
Soil Erosion Modeling	Lørup & Styzcen (1996), Morgan et al. (1999, 1998), Nielsen et al. (1996), Storm et al. (1987)
Agricultural Management	Boegh et al. (2004), Hansen et al. (2001), Refsgaard et al. (1999), Styczen & Storm (1993a,b,c), Thorsen et al. (2001, 1998)
Irrigation	Carr et al. (1993), Jayatilaka et al (1998), Lohani et al. (1993), Singh et al. (1999a &b, 1997)
Remote Sensing – Weather Radar and Satellite	Andersen et al. (2002a &b), Boegh et al. (2004), Butts et al. (2004a &b), Sandholt et al. (2003, 1999)
Land use change and anthropogenic effects	Lørup et al. (1998), Refsgaard & Knudsen (1996), Refsgaard & Sørensen (1997, 1994)
Model Parameter Estimation, Calibration and Validation	Butts et al. (2004), Christiansen & Feyen (2002a & b, 2001), Madsen (2003), Madsen & Kristensen (2002), Mertens et al. (2004), Sonnenborg et al. (2003), Refsgaard (2001a & b, 1997a & b), Refsgaard et al (1998), Refsgaard & Butts (1999), Refsgaard & Knudsen (1996), Vazquez (2003), Vazquez et al. (2002)

The need for fully integrated surface and groundwater models, like MIKE SHE, has been highlighted by several recent studies (e.g. Camp Dresser & McKee Inc., 2001; Kaiser-Hill, 2001; West Consultants Inc. et al., 2001; Kimley-Horn & Assoc. Inc. et al., 2002; Middlemis, 2004, which can all be downloaded from the MIKE SHE web site). These studies compare and contrast available integrated groundwater/surface water codes. They also show that few codes exist that have been designed and developed to fully integrate surface water and groundwater. Further, few of these have been applied outside of the academic community (Kaiser-Hill, 2001).

3 Application Areas in Different Countries

MIKE SHE has been used in a broad range of applications. It is being used operationally in many countries around the world by organizations ranging from universities and research centers to consulting engineers companies (Refsgaard & Storm, 1995). MIKE SHE has been used for the analysis, planning and management of a wide range of water resources and environmental and ecological problems related to surface water and groundwater, such as:

- River basin management and planning
- Water supply design, management and optimization
- Irrigation and drainage
- Soil and water management
- Surface water impact from groundwater withdrawal
- Conjunctive use of groundwater and surface water
- Wetland management and restoration
- Ecological evaluations
- Groundwater management
- Environmental impact assessments
- Aquifer vulnerability mapping
- Contamination from waste disposal
- Surface water and groundwater quality remediation
- Floodplain studies
- Impact of land use and climate change
- Impact of agriculture (irrigation, drainage, nutrients and pesticides, etc.)

Table 1 is a list of some easily accessible references for many of the application areas listed above. The flexibility of MIKE SHE is demonstrated in the next sections by three examples that illustrate surface water modeling for floods (Blue River, USA), groundwater modeling for well head protection areas (Island of Funen, Denmark) and integrated surface and groundwater modeling for wetland management in two very different environments in North America and Africa..

3.1 Distributed Surface Water Modeling for Floods

The 1232 km^2 Blue River Basin is located in south central Oklahoma, USA. The watershed is semi-arid, with a significant number of convective rainfall storms that are characterized by their high intensity and limited lateral extent. This type of rainfall is difficult to characterize with a traditional, sparse network of rain gauges. The Blue River Basin is particularly interesting because of the availability of NEXRAD distributed radar-based rainfall data (see Figure .2a). The NEXRAD data is available at hourly intervals with a spatial resolution of 4 km by 4 km. The Blue River Basin is one of the test basins in the Distributed Modeling Intercomparison Project (DMIP) organised by the Hydrology Lab of the National Weather Service (NWS) (Smith et al., 2004 and www.nws.noaa.gov/oh/hrl/dmip/).

Since, MIKE SHE allows different hydrologic process descriptions to be linked together, multiple combinations of the process models can be evaluated based on essentially the same set of input data. The range of model structures included both lumped and distributed routing, lumped, subcatchment-based and distributed rainfall-runoff models, grid-based modeling using physics-based flow equations, different conceptual process descriptions and lumped, subcatchment-based and gridded NEXRAD radar-rainfall input (see Butts et al., 2004a,b).

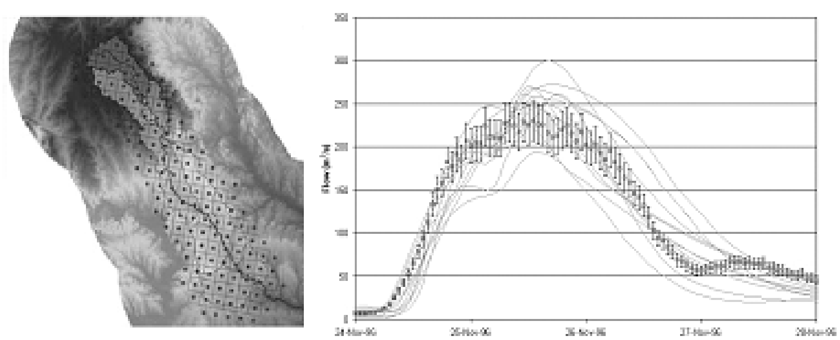

Figure 2. Blue River Basin project: a) The eight subcatchments used in conceptual modelling, as well as the 4-km NEXRAD grid used for the grid-based modelling. b) The output hydrographs from MIKE SHE for each of the different model structures, compared to the measured hydrograph, including the measurement uncertainty.

The results showed that model performance is strongly dependent on model structure (see Figure 2b). Distributed routing and, to a lesser extent, distributed rainfall were found to be the dominant processes controlling simulation accuracy in the Blue River Basin. It was further found that for practical hydrological predictions there are important benefits in exploring different model structures as part of the overall modeling approach.

3.2 Stochastic Delineation of Transient Well Head Protection Areas

Well head protection areas (WHPAs) are a common planning tool for reducing the risk of contamination to drinking water supply wells (Smith et al., 2004). Typical WHPA delineation involves steady-state groundwater flow modeling with deterministic backward particle tracking. This is used to determine the area that contributes water to the well within a prescribed time period- typically two to ten years. The WHPA then becomes subject to land-use restrictions to minimize the risk of contamination. However, WHPAs based solely on steady-state groundwater models ignore or simplify processes outside of the saturated groundwater zone and neglect important dynamic and transient effects.

MIKE SHE is increasingly being used to determine more realistic WHPAs that take into consideration such factors as distributed seasonal variations in ET and net recharge, unsaturated zone storage and delayed recharge, dynamic surface water boundary conditions, high volume recharge during storms, variable pumping rates, and demand and land-use changes. Such models can be used for real-time, on-line management to ensure a safe and continuous water supply.

MIKE SHE was recently used in Denmark, to evaluate the uncertainty associated with WHPA delineation, which is ignored in traditional, deterministic WHPAs delineation. MIKE SHE's automatic calibration and Monte Carlo utilities were used to determine the areas that most likely contribute water to the well and, thus, optimize planning restrictions for stakeholders (see Figure 3).

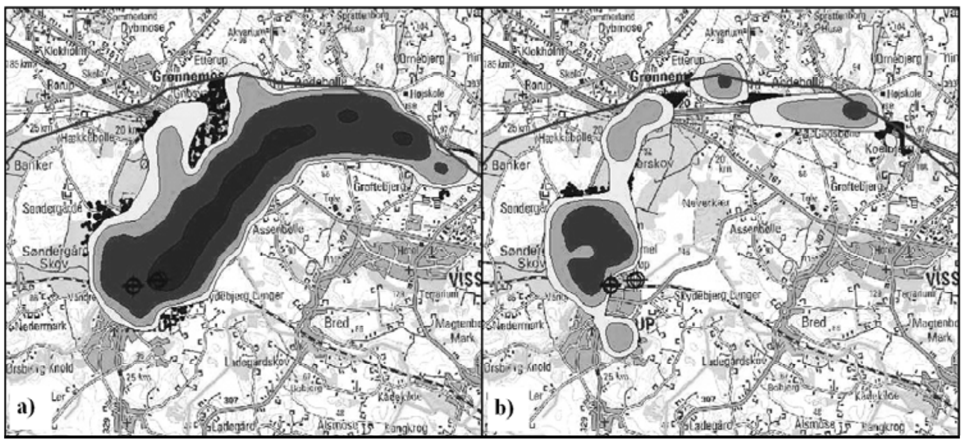

Figure 3. Example Monte Carlo analysis. (a) Probable well field capture zone in lower aquifer. (b) Probable infiltration zones on the ground surface. (85 transient simulations; 14 parameters; Darker areas equal higher probability.)

3.3 Wetland Management

Recent decades have seen significant loss and degradation of wetland areas. There is a growing realization that wetlands are not only important ecological and wildlife areas, but also provide a range of other benefits. Wetlands are sensitive, complex systems with tightly integrated surface water and groundwater. For example, relatively minor changes in groundwater level can have a significant impact on wetland function and extent by altering the groundwater-surface water exchange. Furthermore, the relation between groundwater and surface water is essentially dynamic and dominated by low flow and high flow events.

In the Florida Everglades, there is a pronounced interaction between surface water and groundwater. Nearly all areas of the Florida Everglades are either partially or completely controlled by drainage canals that provide important economic and flood control functions. MIKE SHE is being used extensively in Florida to assess the impacts of irrigation, flood control, and wetland restoration that includes both the surface water and groundwater regimes (see Table 1).
Another major study currently going on to develop a comprehensive, integrated management plan for the conservation and sustainable use of the Okavango Delta and surrounding areas. The Okavango delta is a complicated hydrological system. About 6000 km'2 is permanently flooded swamp with low water depth and extensive surface vegetation. During the flood period the flooded area is almost tripled.In order to establish a prediction model to answer "what-if" question regarding the hydrology in the area i.e. the water balance and especially the groundwater outflow and evapotranspiration, an integrated surface water and groundwater model covering the entire delta and surrounding shall be developed. The integrated model complex based on MIKE SHE and MIKE 11 is used to visualize and quantify the effect of various management options within the Okavango Delta such as: 1) Climate changes; 2) Changes in groundwater exploitation; 3) Dredging of new channels; 4) Cutting of read; and 5) Upstream storage development.

4 Process-based hydrologic modeling

MIKE SHE, in its original formulation, could be characterized as a deterministic, physics-based , distributed model code. It was developed as a fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models. A physics-based code is one that solves the partial differential equations describing mass flow and momentum transfer. The parameters in these equations can be obtained from measurements and used in the model. For example, the St. Venant equations (open channel flow) and the Darcy equation (saturated flow in porous media) are physics-based equations.

There are, however, important limitations to the applicability of such physics-based models. For example,

- it is widely recognized that such models require a significant amount of data and the cost of data acquisition may be high;
- the relative complexity of the physics-based solution requires substantial execution time;
- the relative complexity may lead to over-parameterized descriptions for simple applications; and
- a physics-based model attempts to represent flow processes at the grid scale with mathematical descriptions that, at best, are valid for small-scale experimental conditions.

Therefore, it is often practical to use simplified process descriptions. Similarly, in most watershed problems one or two hydrologic processes dominate the watershed behavior. For example, flood forecasting is dominated by river flows and surface runoff, while wetland restoration depends mostly on saturated groundwater flow and overland flow. Thus, a complete, physics-based flow description for all processes in one model is rarely necessary. A sensible way forward is to use physics-based flow descriptions for only the processes that are important, and simpler, faster, less data demanding methods for the less important processes. The downside is that the parameters in the simpler methods are usually no longer physics meaningful, but must be calibrated-based on experience.

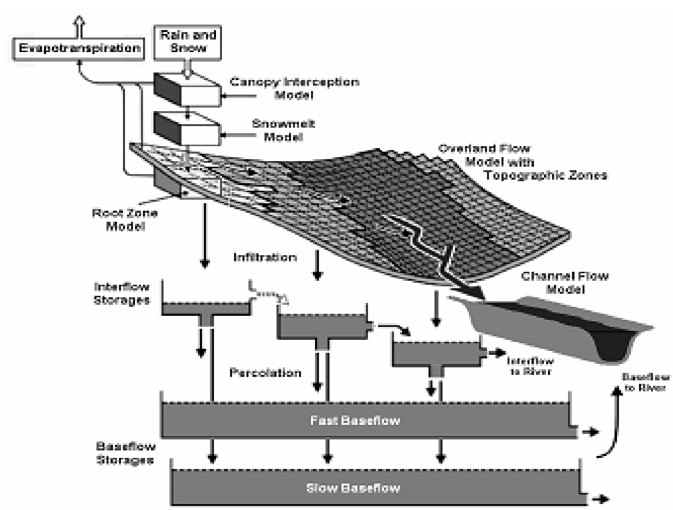

Figure 4. Schematic representation of the conceptual components in MIKE SHE - semi-distributed overland flow and linear reservoir groundwater models.

The process-based, modular approach implemented in the original SHE code has made it possible to implement multiple descriptions for each of the hydrologic processes. In the simplest case, MIKE SHE can use fully distributed conceptual approaches to model the watershed processes (Figure 4). For advanced applications, MIKE SHE can simulate all the processes using physics-based methods. Alternatively, MIKE SHE can combine conceptual and physics-based methods-based on data availability and project needs. The flexibility in MIKE SHE's process-based framework allows each process to be solved at its own relevant spatial and temporal scale. For example, evapotranspiration varies over the day and surface flows respond quickly to rainfall events, whereas groundwater reacts much slower. In contrast, in many non-commercial, research-oriented integrated hydrologic codes (e.g. MODFLOW HMS, Panday et al., 1998; InHM, Sudicky et al., 2002), all the hydrologic processes are solved implicitly at a uniform time step, which can lead to intensive computational effort for watershed scale models.

A deterministic model will be subject to uncertainty. The uncertainty arises because the mathematical process descriptions are not true reflections of the underlying physical processes. Add to this, measurement error, sub-grid scale variability of parameters, and inexact initial and boundary conditions. This inevitably leads to a range of possible models that are equally probable yet may have quite different outcomes.

MIKE SHE includes a set of tools for automatically adjusting model parameters in response to model outcomes (Madsen, 2003). MIKE SHE's auto-calibration tool is based on the global search, Complex Shuffled Evolution (SCE) algorithm. Global search methods are particularly well suited to hydrologic models because the objective function is rarely smooth with respect to the parameter values, which can cause trouble for gradient based methods. MIKE SHE's AUTOCAL tool can calibrate to multiple objective functions, with automatic weighting. Also available is a set of tools for automatically distributing the model simulations across an office network to efficiently take advantage of unused computer resources.

The hydrologic cycle is all about water exchange and the analysis of this exchange is the water budget. Questions regarding sustainability and environmental impacts are directly related to the water budget. Since MIKE SHE includes all of the processes in the hydrologic cycle, MIKE SHE includes a sophisticated water budgeting tool for summarizing, mapping and plotting the exchange of water between all of the hydrologic processes.

5 Looking ahead

MIKE SHE continues to be extended and enhanced by DHI to meet the needs of its growing user community. Some of the more important developments are described below.

MIKE SHE, together with MIKE 11, is being used to meet the growing need for flood modeling, flood forecasting and flood hazard assessment. MIKE SHE, together with MOUSE, is being used to calculate the impacts of urban flooding. However, the propagation of flood waves and detailed 2D surface flow is difficult on flat terrain when infiltration is important. To address this problem, we are linking 2D surface water models (using MIKE 21) to MIKE SHE.

Several initiatives are in progress to keep up with the advances in computer architecture. These include migrating the code to the new 64-bit processors, optimizing the code for parallel processing, adding faster multi-grid solvers, and upgrading the numeric engines to run on alternative operating systems.

The EcoLab tools add complete flexiblity for water quality calculations in surface water. The same flexibility will be available for all of the hydrologic processes in MIKE SHE when the EcoLab toolbox is fully implemented in MIKE SHE.

Significant advances have been made in MIKE 11 to account for a variety of ice conditions, as well as freezing and thawing in the river channel. We are working to add important processes for spring flooding, such as latent heat and the moisture content and temperature of the snow pack, as well as the influence of frozen soils on runoff generation.

Many users want to link MIKE SHE to their own codes to simulate specific processes, such as vegetation growth code, or economic optimization. This will be possible in the near future thanks to the HarmonIT project (www.harmonIT.org) of which DHI is one of the lead partners. The HarmonIT project is an EU-sponsored research initiative to create and prove an Open Modeling Interface (OpenMI), which is a set of standards and tools for linking disparate hydrologic modeling codes together. For example, the OpenMI concept is being used to couple MIKE SHE to meteorological models to examine atmospheric feedbacks in the hydrological cycle.

6 Conclusion

It is no longer acceptable to manage groundwater and surface water independently of one another. Advances in data collection and availability, as well as computer resources, have now made distributed, physics-based watershed modeling feasible in a wide range of applications. MIKE SHE is one of the few commercially available codes that has been widely used for integrated hydrologic modeling. MIKE SHE's process based framework allows each hydrologic process to be represented according to the problem needs at different spatial and temporal scales. This flexibility has allowed MIKE SHE to be applied at spatial scales ranging from single soil profiles, to the field scale, and up to the watershed scale. Furthermore, each process can be represented at different levels of complexity. MIKE SHE has a modern, Windows-based user interface that includes advanced tools for water quality, parameter estimation and water budget analysis. MIKE SHE is continually being developed and extended and will soon be capable of detailed flood modeling, include more advanced water quality models, and be part of a growing community of OpenMI compliant hydrologic modeling tools.

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